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MAGNETIC MONOPOLES

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Abstract. We discuss the experimental situation of direct searches at accelerators for Dirac magnetic monopoles, and in the penetrating cosmic radiation for the superheavy magnetic monopoles predicted by GUT theories. We also discuss the searches for intermediate mass monopoles (which are predicted by theories in extra dimensions), and for nuclearites and Q-balls.

1 Introduction

The magnetic monopole (MM) concept may be traced back to the origin of magnetism, with first accounts in 1269. At the beginning of the 19th century there were discussions and experiments concerning the magnetic content of matter and some speculations about the possible existence of isolated magnetic charges.

In 1931 Dirac introduced the MM in order to explain the quantization of the electric charge, which follows from the existence of at least one free magnetic charge [1]. Dirac established the relationship between the basic elementary electric charge e and the basic magnetic charge g: $eg = n\hbar c/2$, where n is an integer; $g_D = \hbar c/2e$ is called the unit Dirac charge. There was no prediction for the MM mass.

From 1931 many searches for "classical Dirac monopoles" were carried out at every new accelerator; the searches were made with relatively simple set–ups.

In 1974 it was realized that the electric charge is naturally quantized in unified gauge theories of the basic interactions and that such unified theories imply the existence of MMs, with calculable properties. In the context of the

Grand Unification Theory of strong and electroweak interactions (GUT), the MMs appear at the phase transition corresponding to the spontaneous breaking of the unified group into subgroups, one of which is U(1) [2]. The MM mass is related to the mass m_X of the carriers X of the unified interaction, $m_M \geq m_X/G$, where G is the dimensionless unified coupling constant at E $\simeq m_X$. In GUT one has $m_X \simeq 10^{14} - 10^{15}$ GeV and $G \simeq 0.025$; consequently $m_M > 10^{16} - 10^{17}$ GeV. This is an enormous mass: MMs cannot be produced at any man–made accelerator, existing or conceivable. They could only be produced in the first instants of our universe and they may be searched for as relic particles in the penetrating cosmic radiation.

Larger MM masses are expected if gravity is brought into the unification picture and in some SuperSymmetric theories.

The application of the simplest GUTs to the standard early universe scenario yields too many monopoles, while inflationary scenarios lead to a very small number. Thus gauge theories of the unified interactions demand the existence of MMs; however, the prediction of the monopole mass is uncertain by several orders of magnitude, the magnetic charge could be anywhere between one and several Dirac units, and the expected flux could vary from a very small value to a sizeable and observable one.

Intermediate mass monopoles (IMMs) could have been produced in later phase transitions in the early universe, in which a semisimple gauge group yields a U(1) factor at a lower energy scale. IMMs with masses around $10^7 \div 10^{13}$ GeV have been proposed [3, 4]. Superheavy MMs and IMMs are topological point defects; an undesirable large number of relatively light monopoles may be gotten rid of by means of higher dimensional topological defects (strings, walls).

One of the recent interests in relatively low mass MMs is connected also with the possibility that relativistic MMs could be the source of the highest energy cosmic rays, with energies larger than 10^{20} eV [4]. Intermediate mass MMs could be accelerated to relativistic velocities in one coherent domain of the galactic magnetic field, or in the intergalactic field, or in several astrophysical sites, like in the magnetic fields of Active Galactic Nuclei (AGN) and even of neutron stars.

The lowest mass MM is expected to be stable, since magnetic charge should be conserved like electric charge. Therefore, the MMs produced in the early universe should still exist as cosmic relics, whose kinetic energy has been strongly affected by their travel through galactic and intergalactic magnetic fields.

The most direct method of searching for GUT monopoles is to search for them in the penetrating cosmic radiation. GUT poles should be characterized by low velocities and relatively large energy losses. Instead IMMs should be relativistic and should be searched for at high altitude laboratories, and possibly at sea level via Cherenkov radiation.

In the following we shall summarize the basic properties of MMs, and of their interactions in matter. Searches for classical, GUT and intermediate mass monopoles are then described. Monopole catalysis of proton decay is discussed

in Sect. 9. An outlook and conclusions are given in Sect. 12. We shall also briefly discuss searches for nuclearites and Q-balls.

2 Main properties of magnetic monopoles

The consequences of the Dirac relation, $eg = n\hbar c/2$, are summarized here.
- *Magnetic charge.* If n =1 and if the basic electric charge is that of the electron, then the basic magnetic charge is $g_D = \hbar c/2e = 137e/2 = 3.29 \times 10^{-8}$ CGS.
- *Coupling constant.* In analogy with the fine–structure constant, $\alpha = e^2/\hbar c \simeq 1/137$, the dimensionless magnetic–coupling constant is $\alpha_g = g_D^2/\hbar c \simeq 34.25$.
- *Energy W acquired in a magnetic field B*: $W = ng_D B\ell = n20.5$ keV/G cm. In a coherent galactic–length, $\ell \simeq 1$ kpc, and $B \simeq 3$ μG, the energy gained by a monopole is: $W_G = WB\ell \simeq 1.8 \times 10^{11}$ GeV.
- *Energy losses in matter.* A fast MM with magnetic charge g_D and velocity $v = \beta c$ behaves like an equivalent electric charge $(Ze)_{eq} = g_D\beta$.
- *Trapping of MMs in ferromagnetic materials.* MMs may be trapped in ferromagnetic materials by an image force, which may reach the value of $\simeq 10$ eV/Å.
- *Mass and spatial structure of a GUT pole* (with $m_M \simeq 10^{17}$ GeV). It may be pictured as having: (i) a core with radius $r_c \simeq 1/m_X \simeq 10^{-29}$ cm; (ii) a region up to $r \simeq 10^{-16}$ cm, where virtual W^+, W^- and Z^o may be present; (iii) a confinement region with $r_{conf} \simeq 1$ fm; (iv) a fermion–antifermion condensate region up to $r_f \simeq 1/m_f$; the condensate may contain 4–fermion baryon–number–violating terms; (v) for $r \geq 3$ fm a MM behaves as a point particle which generates a field $B = g/r^2$ (see Fig. 1) [5].
- Electrically charged monopoles (dyons) may arise as quantum–mechanical excitations of GUT poles or as M–p, M-nucleus composites.
- The structure of an IMM would be similar to that of a GUT monopole, but the core would be larger (since R $\sim 1/m_M$) and the outer cloud would not contain 4–fermion baryon–number–violating terms.

3 Interactions of magnetic monopoles with matter

It is important to know whether the quantity and quality of energy lost by a MM in a particle detector is adequate for its detection. Classical poles and IMMs can be accelerated to relativistic velocities. Instead GUT poles have large masses and are expected to have relatively low velocities, $10^{-4} < \beta < 10^{-1}$, $\beta = v/c$. The interaction of the MM magnetic charge with nuclear magnetic dipoles could lead to the formation of M–nuclei bound systems. This may affect the energy loss in matter and the cross–section for MM catalysis of proton decay. A monopole–proton bound state may be produced via radiative capture,

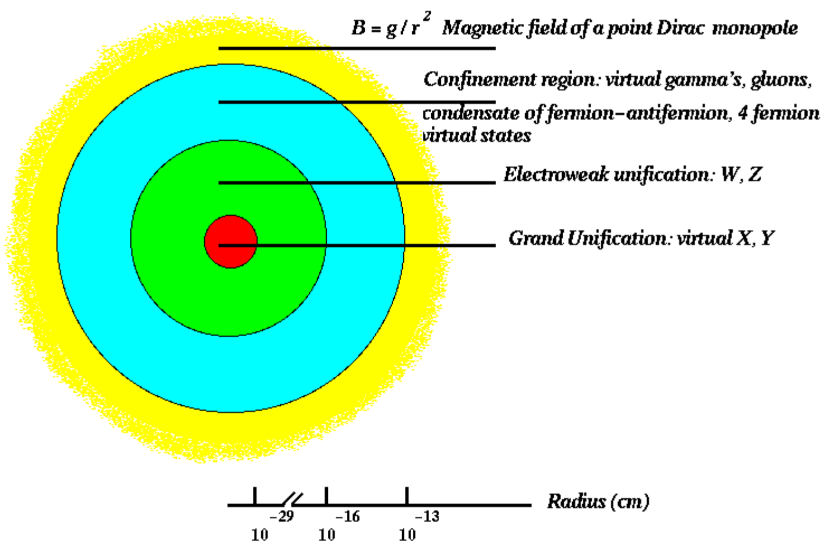

Figure: 1 Structure of a GUT monopole. The various regions correspond to: (i) Grand Unification ($r \sim 10^{-29}$ cm; inside this core one finds virtual X and Y particles); (ii) electroweak unification ($r \sim 10^{-16}$ cm; inside this region one finds virtual $W^{\pm}$ and Z^0); (iii) confinement region ($r \sim 10^{-13}$ cm; inside one finds virtual γ, gluons and a condensate of fermion-antifermion pairs and 4-fermion virtual states); (iv) for $r >$ few fm one has the field of a point magnetic charge.

$M+p \rightarrow (M+p)_{bound}+\gamma$. Monopole–nucleus bound states may exist for nuclei with a large gyromagnetic factor.
- *Energy losses of fast poles.* A fast MM moving with velocity $v > 10^{-2}c$ behaves like an equivalent electric charge $(Ze)^2_{eq} = g^2\beta^2$.
- *Energy losses of slow monopoles (*$10^{-4} < \beta < 10^{-2}$*).* For slow particles it is important to distinguish the energy lost in ionization or excitation of atoms and molecules of the medium ("electronic" energy loss) from that lost to yield kinetic energy of recoiling atoms or nuclei ("atomic" or "nuclear" energy loss). Electronic energy loss predominates for electrically or magnetically charged particles for $\beta > 10^{-2}$. The dE/dx of MMs with $10^{-4} < \beta < 10^{-3}$ is mainly due to excitations of atoms. A monopole passing within an atom like $^4He_2$ may produce level mixings and crossings (*Drell effect*) [6]. The effect may be used for practical detection by observing the ionization caused by the energy transfer from the excited He atoms to complex molecules with a small ionization potential (*Penning effect*).
- *Energy losses at very low velocities.* MMs with $v < 10^{-4}c$ cannot excite atoms; they can only lose energy in elastic collisions with atoms or with nuclei. The energy is released to the medium in the form of elastic vibrations and/or infra–red radiation.

Fig. 2 gives a sketch of the energy losses in liquid hydrogen of a $g = g_D$ MM vs its β.
- *Energy losses in superconductors.* If a pole passes through a superconductor, there will be a magnetic flux change of $\phi_B = 2\pi\hbar c/e$ (two flux quanta of superconductivity), yielding $dE/dx \simeq 42$ MeV/cm, which is β-independent.
- *Energy losses of MMs in celestial bodies.* For $\beta < 10^{-4}$ the main energy losses in the earth are due to : i) pole–atom elastic scattering, ii) eddy current losses, iii) nuclear stopping power. The earth should stop GUT MMs with $\beta \leq 10^{-4}$. From similar estimates for other celestial bodies one concludes that poles may be stopped if they have
Moon: $\beta \leq 5 \times 10^{-5}$, Earth: $\beta \leq 10^{-4}$, Jupiter: $\beta \leq 3 \times 10^{-4}$, Sun: $\beta \leq 10^{-3}$.

4 Monopole detectors

- *Superconducting induction devices.* This method of detection is based only on the long–range electromagnetic interaction between the magnetic charge and the macroscopic quantum state of a superconducting ring. A moving MM induces in the ring an electromotive force and a current (Δi). For a coil with N turns and inductance L, $\Delta i = 4\pi N n g_D/L = 2\Delta i_o$, where Δi_o is the current change corresponding to a change of one unit in the flux quantum of superconductivity (in practice $\Delta i \simeq 10^{-9}$A, $L \simeq$ few μH, energy $\simeq 4 \times 10^{-17}$ erg). A superconducting induction detector, consisting of a detection coil coupled to a SQUID (Superconducting Quantum Interferometer Device), should be sensitive

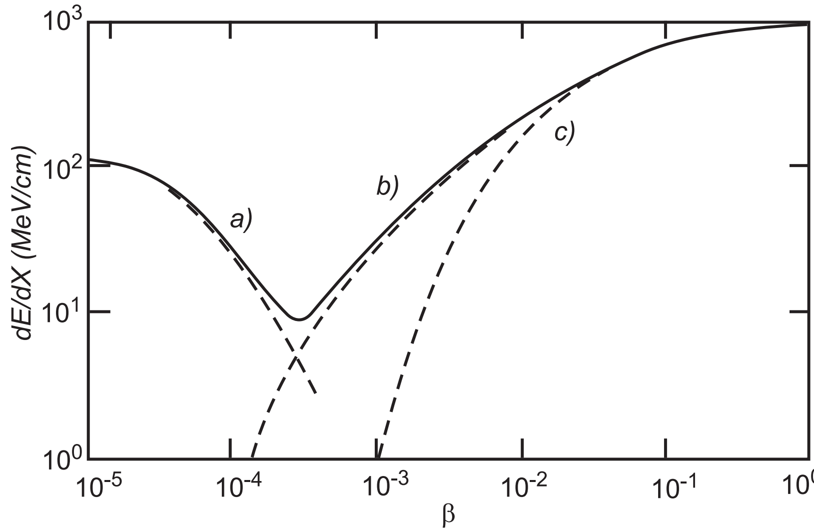

Figure 2: The energy losses, in MeV/cm, of $g = g_D$ MMs in liquid hydrogen as a function of β. Curve a) corresponds to elastic monopole–hydrogen atom scattering; curve b) corresponds to interactions with level crossings; curve c) describes the ionization energy loss.

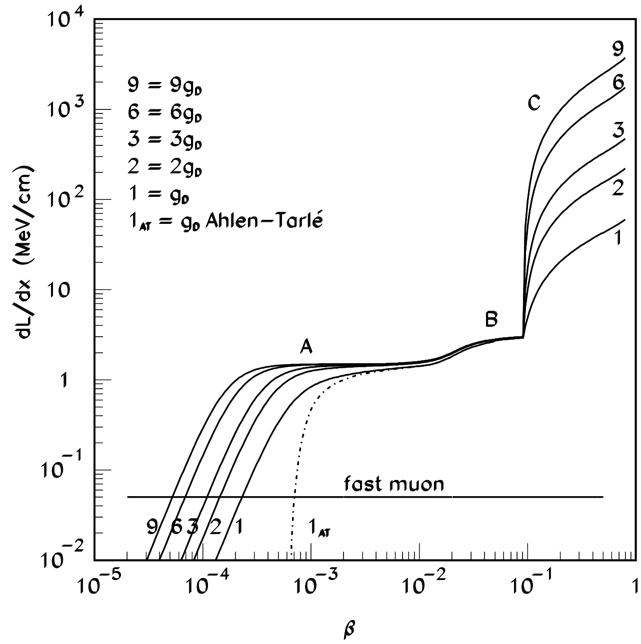

Figure 3: Light yield of MMs in the plastic scintillator NE110 ($\rho = 1.032$ g/cm^3) and in the MACRO liquid scintillator ($\rho = 0.86$ g/cm^3), versus β for $g = ng_D$ magnetic charge with n =1–9.

to MMs of any velocity.
- *Scintillation counters.* Many searches have been performed using excitation loss techniques. The light yield from a MM in the NE110 scintillator, is shown in Fig. 3 [7]. Curves for a bare $g = ng_D$ monopole with n=1–9 are given. Note the presence of a threshold at $\beta \sim 10^{-4}$, above which the light signal is large compared to that of a relativistic muon. The light yield in Fig. 3 shows the saturation effect present in solid materials at medium velocities. For $\beta > 0.1$ the light yield increases because of the production of many delta rays. Direct measurements by Ficenec et al. [8] from $n-p$ elastic scattering in liquid scintillators proved the sensitivity to slow protons down to $\beta \simeq 10^{-4}$.
- *Gaseous detectors.* Gaseous detectors of various types have been used. MACRO used limited streamer tubes, in units of 8 individual tubes [9], each equipped with readouts for the wires and pickup strips, for two–dimensional localization. The gas was 73% helium and 27% n–pentane. This allows exploitation of the Drell and Penning effects: a magnetic monopole leaves the helium atoms in a metastable excited state (He*) with an excited energy of about 20 eV. The ion-

ization potential of n–pentane is about 10 eV; hence, the Penning effect converts the energy of the He* into ionization of the n–pentane molecule.

5 Searches for "classical" Dirac monopoles

We shall consider as "classical" Dirac monopoles those MMs of relatively low mass which could be produced at accelerators.
- *Accelerator searches.* If MMs could be produced at high–energy accelerators, they would be relativistic and would ionize heavily. Examples of direct searches are scintillation counter searches and the experiments performed with nuclear track detectors where data taking is integrated over periods of months. Experiments at the Fermilab $\overline{p}p$ collider established cross section upper limits of $\sim 3 \times 10^{-32}$ cm^2 for MMs with masses up to 850 GeV. Searches at e^+e^- colliders exclude masses up to 45 GeV [10]. An example of indirect searches is the experiment at the CERN SPS; the 450 GeV protons interacted in a series of targets made of ferromagnetic tungsten powder. Later on the targets were placed in front of a pulsed solenoid with a field $B \sim 200$ kG, large enough to extract and accelerate the MMs, to be detected in nuclear emulsions and in CR39 sheets [10].
- *Multi–γ events.* Five peculiar photon shower events, found in nuclear plates exposed to high–altitude cosmic rays, are characterized by an energetic narrow cone of tens of photons, without any incident charged particle. The total energy in the photons is of the order of 10^{11} GeV. The small radial spread of photons suggests a c.m. $\gamma > 10^3$. The energies of the photons in the overall c.m. system are small, too low to have π^o decays as their source. One possible explanation of these events could be the following: a high–energy γ–ray, with energy $> 10^{12}$ eV, produces in the plate a pole–antipole pair, which then suffers bremsstrahlung and annihilation producing the final multi–γ events. ISR experiments, at $\sqrt{s} =$ 53 GeV, placed a cross–section upper–limit of 10^{-37} cm^2 for multi–γ events [10].
- *Searches in bulk matter.* Classical MMs could be produced by cosmic rays and could stop at the surface of the earth, where they could be trapped in ferromagnetic materials. It is improbable that GUT poles would stop close to the surface of the earth. A search for MMs in bulk matter used a total of 331 kg of material, including meteorites, schists, ferromanganese nodules, iron ore and other materials. The detector was a superconducting induction coil connected to a SQUID. The material was passed at constant velocity through the magnet bore. The passage of a MM trapped in a sample would cause a jump in the current in the superconducting coil. From the absence of candidates the authors conclude that the monopole/nucleon ratio in the sample is $< 1.2 \times 10^{-29}$ at 90% C.L.

Most of the searches for classical MMs performed until 1981 were not relevant to the question of the existence of very massive poles. Ruzicka and Zrelov summarized all searches for classical monopoles performed before 1980 [11].

6 Cosmological and astrophysical bounds on GUT poles

Rough, order of magnitude upper limits for a GUT monopole flux in the cosmic radiation were obtained on the basis of cosmological and astrophysical considerations.

- *Limit from the mass density of the universe.* This bound may be obtained requiring that the present MM mass density be smaller than the critical density ρ_c of the universe. For $m_M \simeq 10^{17}$ GeV one has the following limit: $F = \frac{n_M c}{4\pi}\beta < 3 \times 10^{-12} h_0^2 \beta$ (cm^{-2}s^{-1}sr^{-1}). It is valid for poles uniformly distributed in the universe. If poles are clustered in galaxies the flux limit could be few orders of magnitude larger.

- *Limit from the galactic magnetic field. The Parker limit.* The magnetic field in our Galaxy of $\sim 3\mu$ G is stretched in the direction of the spiral arms; it is probably due to the non–uniform rotation of the Galaxy. This mechanism generates a field with a time–scale approximately equal to the rotation period of the Galaxy ($\tau \sim 10^8$ yr). Since MMs are accelerated in magnetic fields, they gain energy, which is taken from the stored magnetic energy. An upper bound for the monopole flux may by obtained by requiring that the kinetic energy gained per unit time by MMs be less than or equal to the magnetic energy generated by the dynamo effect. This yields the so–called Parker limit [12]. The original limit, $F < 10^{-15}$ cm^{-2} s^{-1} sr^{-1}, was re–examined to take account of the almost chaotic nature of the galactic magnetic field, with domain lengths of about $\ell \sim 1$ kpc; the limit becomes mass dependent [12]. More recently an extended Parker bound was obtained by considering the survival of an early seed field [13]. The result was $F \leq 1.2 \times 10^{-16}(m_M/10^{17}GeV)$ cm^{-2} s^{-1} sr^{-1}.

- *Limit from the intergalactic field.* Assuming the existence in the local group of galaxies of an intergalactic field $B_{IG} \sim 3 \times 10^{-8}\ G$ with a regeneration time $\tau_{IG} \sim 10^9\ y$ and applying the same reasoning discussed above, a more stringent bound is obtained; the limit is less reliable because the intergalactic field is less known.

- *Limits from peculiar A4 stars and from pulsars.* Peculiar A4 stars have their magnetic fields ($B \sim 10^3\ G$) in the direction opposite to that expected from their rotation. A MM with $\beta \leq 10^{-3}$ would be stopped in A4 stars; thus the number of MMs in the star would increase with time (neglecting $M\overline{M}$ annihilation inside the star). The poles could be accelerated in the magnetic field, which would therefore decrease with increasing time. Repeating the Parker argument, one may obtain strong limits, but it is not clear how good are all the assumptions made. With similar considerations applied to the superconducting core of neutron stars, the field survival of a pulsar gives an upper limit of the monopole flux in the neighbourhood of the pulsar. The limit would be particulary stringent for pulsar PSR 1937+214.

7 Searches for supermassive GUT monopoles

A flux of cosmic GUT supermassive magnetic monopoles may reach the earth and may have done so for the whole life of the earth. The velocity spectrum of these MMs could be in the range $3 \times 10^{-5} < \beta < 0.1$, with possible peaks corresponding to the escape velocities from the earth, the sun and the galaxy. Searches for such MMs in the penetrating cosmic radiation have been performed with superconducting induction devices whose combined limit is at the level of $2 \times 10^{-14}\ cm^{-2}\ s^{-1}\ sr^{-1}$, independent of β. Several direct searches were performed above ground and underground using scintillators, gaseous detectors and nuclear track detectors (mainly CR39). The largest array was the Ohya one, with S=2000 m^2 of nuclear track detectors [14]. The most complete search was performed by the MACRO detector, with three different types of subdetectors and with an acceptance of about 10,000 m^2sr for an isotropic flux [15]. No monopoles have been detected; the present 90% C.L. flux limits are shown in Fig. 4 vs β [16]. The limits are at the level of $2 \times 10^{-16}\ cm^{-2}\ s^{-1}\ sr^{-1}$.

Some indirect searches used ancient mica, which has a high threshold. The mica experiment scenario assumes that a bare monopole passing through the earth captures an aluminium nucleus and drags it through subterranean mica causing a trail of lattice defects. As long as the mica is not reheated, the damage trail will survive. The mica pieces analyzed are small (13.5 and 18 cm^2), but should have been recording tracks since they cooled, about $4 \div 9 \times 10^8$ years ago. The upper–limit fluxes are at the level of 10^{-17} cm^{-2} $s^{-1}sr^{-1}$ for $10^{-4} < \beta < 10^{-3}$ [17]. There are many reasons why these indirect experiments might not be sensitive. For example, if MMs have a positive electric charge or have protons attached then Coulomb repulsion could prevent capture of heavy nuclei.

8 Intermediate mass magnetic monopoles

Relativistic magnetic monopoles with intermediate masses, $10^5 < m_M < 10^{12}$ GeV, could be present in the cosmic radiation. Detectors at the earth surface would be capable to detect MMs coming from above if they have masses larger than $\sim 10^5 - 10^6$ GeV, see Fig. 5 [18]; lower mass monopoles may be searched for with detectors located at high mountain altitudes, or even higher, in balloons and in satellites. Few experimental results are available [19]. The limit from the AMANDA experiment under ice at the south pole is shown in Fig. 4 [20].

The SLIM experiment is searching for IMMs with nuclear track detectors at the Chacaltaya high altitude lab (5230 m above sea level) [24].

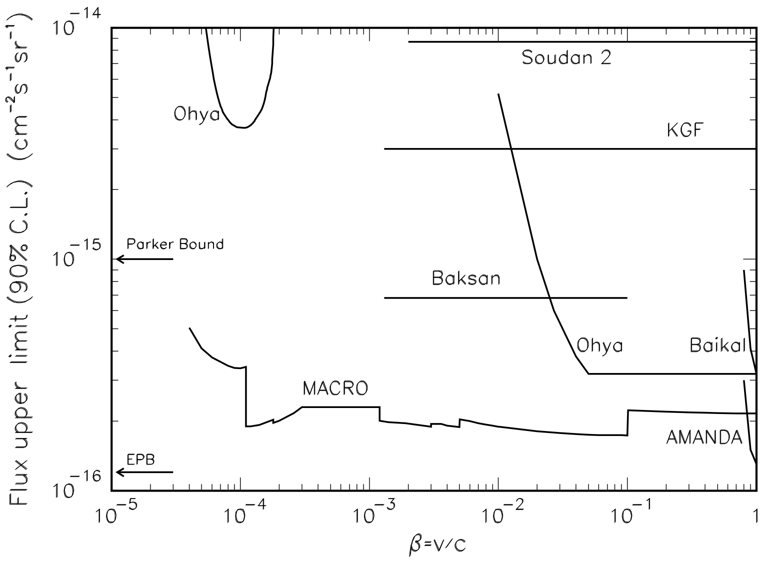

Figure 4: Compilation at 90% C.L. of direct experimental upper limits on an isotropic MM flux reaching detectors at the earth surface or underground.

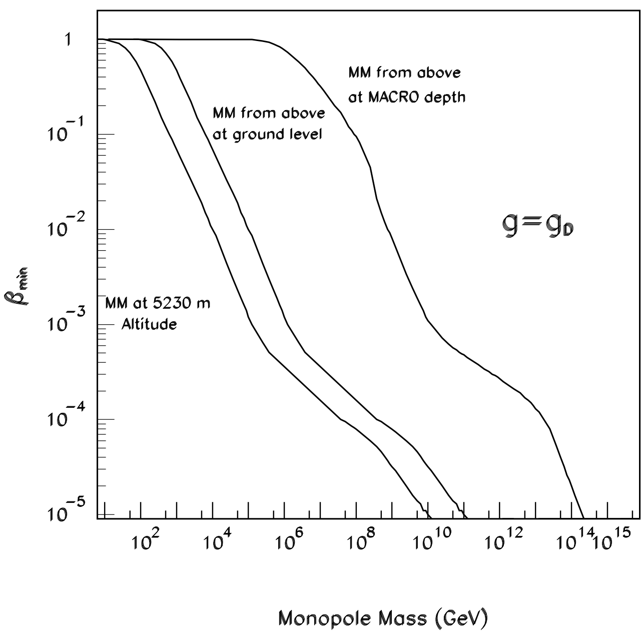

Figure 5: Accessible region in the plane (mass, β) for monopoles with magnetic charge $g = g_D$ from above for an experiment at an altitude of 5230 m, at sea level and for an underground detector at the Gran Sasso Lab (at an average depth of 3700 hg/cm^2).

9 Monopole catalysis of proton decay

A GUT pole may catalyze proton decay, $p + M \to M + e^+ + \pi^0$. The cross–section could be comparable with that of ordinary strong interactions, if the MM core is surrounded by a fermion–antifermion condensate (Fig. 1), with some $\Delta B \neq 0$ terms extending up to the confinement region. Thus MMs may capture a proton or a nucleus and lead to the catalysis reaction. For spin 1/2 nuclei, like aluminium, there should be an enhancement in the cross section over that for free protons. Instead for spin–0 nuclei there should be a β–dependent suppression. For oxygen the suppression factor could be of the order of 10^{-2} at $\beta = 10^{-3}$, $\simeq 10^{-5}$ at $\beta = 10^{-4}$.

If the $\Delta B \neq 0$ cross–section for MM catalysis of proton decay were large, then a monopole would trigger a chain of baryon "decays" along its passage through a large detector [16].

It should be noted that if MMs have a large catalysis cross–section then the monopole–proton composites could be unstable.

- *Astrophysical limits from monopole catalysis of nucleon decay.* The number of MMs inside a star or a planet should increase with time, due to a constant capture rate and a small pole–antipole annihilation rate. The catalysis of nucleon decay by MMs could be another source of energy for these astrophysical bodies. The catalysis argument, applied to the protons of our sun, leads to the possibility that the sun could emit high energy electron neutrinos. The ν_e's could be detected through their elastic scattering on electrons. The Kamiokande experiment quoted the limit $F < 8 \times 10^{-10} \beta^2$ if the monopole catalysis cross–section is 1 mb. From such limits one could place a limit on the number of poles in the sun, of less than 1 pole per 10^{12} g of solar material [10].

A speculative upper bound on the total number of MMs present inside the earth can be made assuming that the energy released by MM catalysis of nucleon decay in the earth does not exceed the surface heat flow.

10 Nuclearites

Strangelets, Strange Quark Matter (SQM) should consist of aggregates of u, d and s quarks in almost equal proportions (the number of s quarks should be lower than the number of u or d quarks; thus the SQM should have a positive charge [21]. The SQM should be a colour singlet; thus it should have only integer electric charge. The overall neutrality of SQM is ensured by an electron cloud which surrounds it, forming a sort of atom. (We shall use the word nuclearite to denote the core+electron system).

Strangelets could have been produced shortly after the Big Bang and may have survived as remnants; they could also appear in violent astrophysical processes, such as neutron star collisions. Nuclearites should have a constant density [22], $\rho_N = M_N/V_N \simeq 3.5 \times 10^{14}$ g cm^{-3}, somewhat larger than that of

atomic nuclei, and they should be stable for all baryon numbers in the range between ordinary heavy nuclei and neutron stars ($A \sim 10^{57}$) [22]. Nuclearites could contribute to the cold dark matter.

The relation between mass and size of nuclearites is illustrated in Fig. 6.

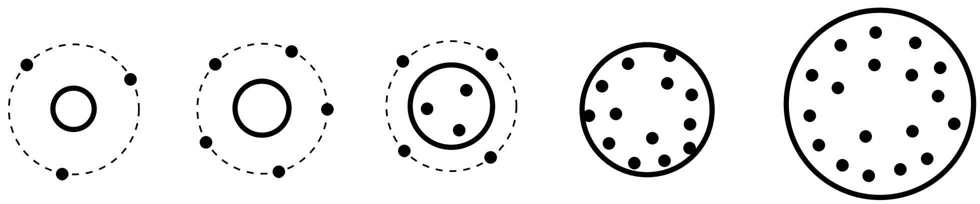

Figure 6: Dimensions of the quark bag (R_N) and of the core+electrons system (nuclearite). The radii presented here (in a logarithmic scale) refer to the nuclearite quark bag core. For nuclearite masses smaller than 10^9 GeV/c^2, the entire electron cloud is outside the quark bag and the core+electrons system has a global size of approximately 10^5 fm = 1 Å; for $10^9 < M_N < 10^{15}$ GeV/c^2 the electrons are partially inside the core; for $M_N > 10^{15}$ GeV/c^2 all electrons are inside the core. The black dots indicate the electrons, the quark bag border is indicated by thick solid lines; the border of the core+electronic cloud system for relatively small masses is indicated by the dashed lines.

The main energy loss mechanism for low velocity nuclearites passing through matter is that of atomic collisions. While traversing a medium the nuclearites should displace the matter in their path by elastic or quasi-elastic collisions with the ambient atoms [22]. The energy loss rate is large; therefore nuclearites should be easily detectable by detectors (like scintillators and CR39 nuclear track detectors) used for MM searches.

Nuclearites are expected to have typical galactic velocities, $\beta \sim 10^{-3}$. For such velocities, nuclearites with masses larger than 0.1 g could traverse the earth. Most nuclearite searches were obtained as byproducts of superheavy magnetic monopole searches. The cosmic ray flux limits are therefore similar to those obtained for MMs.

The most relevant direct flux upper limits for nuclearites come from three large area experiments: the first two use CR39 nuclear track detectors; one experiment was performed at mountain altitude [19], the second at a depth of $10^4 g\ cm^{-2}$ in the Ohya mines [14]; the third experiment was MACRO which used liquid scintillators besides nuclear track detectors [23]. A fourth experiment (SLIM) is deployed at high altitudes [24]. Indirect experiments using old

mica samples could yield the lowest flux limits, but they are affected by inherent systematic uncertainties [25]. Some exotic cosmic ray events were interpreted as due to incident nuclearites, for example the "Centauro" events and the anomalous massive particles [33]. The interpretation of those possible signals are not unique and the used detectors are not redundant enough to reach a conclusion.

In Fig. 7 is presented a compilation of limits for a flux of downgoing nuclearites compared with the dark matter limit, assuming a velocity at ground level $\beta = v/c = 2 \times 10^{-3}$. This speed corresponds to nuclearites of galactic or extragalactic origin. In the figure the MACRO limit was extended above the dark matter bound, in order to show the transition to an isotropic flux for nuclearite masses larger than 0.1 g ($\sim 10^{23}$ GeV).

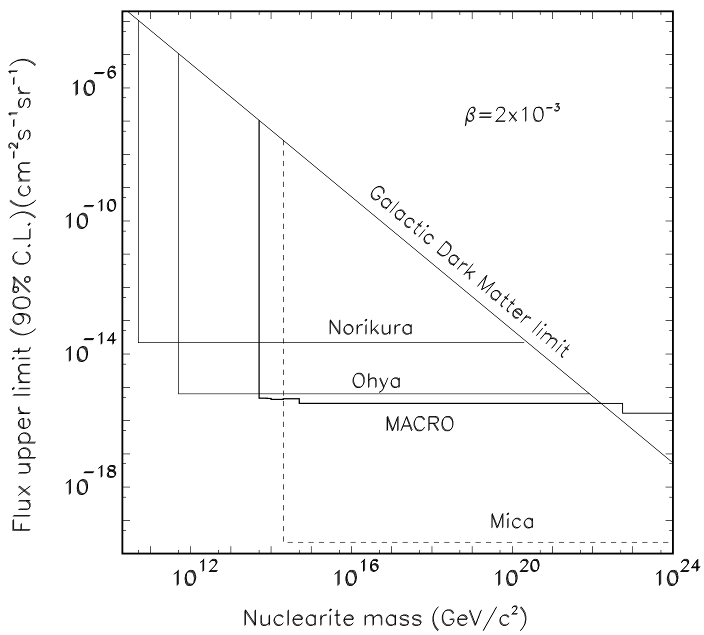

Figure 7: 90% C.L. flux upper limits versus mass for nuclearites with $\beta = 2 \times\ 10^{-3}$ at ground level. These nuclearites could have galactic or extragalactic origin. The limits are from MACRO [16], from Refs. [19] ("Nakamura"), [15] ("Orito") and the indirect Mica limits of Ref. [17].

11 Q-balls

Q-balls should be aggregates of squarks $\tilde{q}$, sleptons $\tilde{l}$ and Higgs fields [25, 26]. The scalar condensate inside a Q-ball core has a global baryon number Q (and may be also a lepton number). Protons, neutrons and may be electrons could be absorbed in the condensate.

There could exist neutral and charged Q-balls: Supersymmetric Electrically Neutral Solitons (SENS), which do not have a net electric charge, are generally massive and may catalyse proton decay. SENS may obtain an integer positive electric charge absorbing a proton in their interactions with matter yielding SECS (Supersymmetric Electrically Charged Solitons), which have a core electric charge, have generally lower masses and the Coulomb barrier could prevent the capture of nuclei. SECS have only integer charges because they are colour singlets. Some Q-balls which have sleptons in the condensate can also absorb electrons. The squarks $\tilde{q}$ inside the scalar potential bag should have essentially zero masses.

A SENS which enters the earth atmosphere could absorb a nucleus of nitrogen which would give it the positive charge of +7 (SECS with $Z = +7$). Other nuclear absorptions are prevented by Coulomb repulsion. If the Q-ball can absorb electrons at the same rate as protons, the positive charge of the absorbed nucleus may be neutralized by the charge of absorbed electrons. If, instead, the absorption of electrons is slow or impossible, the Q-ball carries a positive electric charge after the capture of the first nucleus in the atmosphere.

The Q-balls could be possible cold dark matter candidates. Flux limits on Q-balls may come from astrophysical dark matter limits. SECS with $\beta \simeq 10^{-3}$ and $M_Q < 10^{13}$ GeV/c^2 could reach an underground detector from above, SENS also from below [27, 28]. SENS may be detected by their almost continuous emission of charged pions (energy loss of about 100 GeV g^{-1}cm^2), while SECS may be detected by their large energy losses yielding light in scintillators, and possibly ionization.

12 Conclusions. Outlook

1. Direct and indirect searches for classical Dirac monopoles have placed mass limits at the level of $m_M > 850$ GeV. Future improvements could come from experiments at the LHC.

2. Many searches have been performed for superheavy GUT monopoles in the penetrating cosmic radiation. The flux limits are at the level of $\Phi \leq 2 \times 10^{-16} cm^{-2} s^{-1} sr^{-1}$ for $\beta \geq 3 \times 10^{-5}$. It would be difficult to do much better since one would require detectors of considerably larger areas. Or one has to devise new techniques.

3. Present limits on Intermediate Mass Monopoles are relatively poor. Experiments at high altitudes and at neutrino telescopes may be able to improve

the situation.

4. For nuclearites with typical galactic velocities one may repeat the considerations made in points 2 and 3. For them the searches at high altitude labs are very important.

5. For Q-balls the situation is less clear, though some considerations similar to those of point 4 can be made.

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[1]

References

[1] P. A . M. Dirac, Proc. R. Soc. London 133 (1931) 60; Phys. Rev. 74 (1948) 817.

[2] G. 't Hooft Nucl. Phys. B29 (1974) 276; A.M. Polyakov, JETP Lett. 20 (1974) 194; G. Giacomelli, Riv. Nuovo Cimento 7 (1984) N.12,1; N. S. Craigie, G. Giacomelli, W. Nahm and Q. Shafi, Theory and Detection of Magnetic Monopoles in Gauge Theories, World Scientific, Singapore (1986).

[3] G. Lazarides et al., Phys. Rev. Lett. 58 (1987) 1707; Q. Shafi (Proton decay, magnetic monopoles and extra dimensions), invited paper at the Neutrino Telescope Workshop, Venice, March 2001; T. W. Kephart and Q. Shafi (Family unification, exotic states and magnetic monopoles), hep-ph/0105237 (2001).

[4] T. W. Kephart and T. J. Weiler, Astrop. Phys. 4 (1996) 217; C. O. Escobar and R. A. Vazquez, Astrop. Phys. 10 (1999) 197; V. Berezinsky et al., (High energy particles from monopoles connected by strings) INFN/TH-97/03 (1997).

[5] D. Bakari et al. (Magnetic Monopoles, Nuclearites, Q-balls: a qualitative picture), hep-ex/0004019 (2000).

[6] G. F. Drell et al., Nucl. Phys. B209 (1982) 45.

[7] J. Derkaoui et al., Astrop. Phys. 10 (1999) 339.

[1] A bibliography compilation on magnetic monopoles updated to the end of 1999 can be found in Ref. [29].

[8] D. J. Ficenec et al., Phys. Rev. D36 (1987) 311.

[9] S. P. Ahlen et al., MACRO Coll., Nucl. Instr. & Meth. A324 (1993) 337.

[10] G. Giacomelli (MM searches), Lectures at the Lake Louise Workshop (1994); G. Giacomelli and L. Patrizii (Magnetic Monopoles), Proceedings of the 5th School on Non-Accelerator Particle Astrophysics, ICTP, Trieste, Italy, 1998; hep-ex/0002032 (2000).

[11] J. Ruzicka and V. P. Zrelov JINR-1-2-80-850 (1980).

[12] E. N. Parker, Ap. J. 160 (1970) 383; M. S. Turner et al., Phys. Rev. D26 (1982) 1296.

[13] F. C. Adams et al., Phys. Rev. Lett. 70 91993) 2511.

[14] S. Orito at al. Phys. Rev. Lett. 66 (1991) 1951.

[15] M. Ambrosio et al., MACRO Coll., Phys. Rev. Lett. B406 (1997) 249; hep-ex/0009002.

[16] M. Sitta for the MACRO Coll. (Search for massive rare particles with MACRO), Proceedings of 27th ICRC, Hamburg, Germany, 2001.

[17] P. B. Price, Phys. Rev. D38 (1988) 3813; D. Ghosh and S. Chatterjea, Europhys. Lett. 12 (1990) 25.

[18] J. Derkaoui et al., Astrop. Phys. 9 (1998) 173.

[19] S. Nakamura et al. Phys. Lett. B263 (1991) 529.

[20] G. Domogatsky for the Baikal Coll., (The Baikal Neutrino Project, Status report) XIX Int. Conf. on Neutrino Physics and Astrophysics, Sudbury, Canada (2000).

[21] E. Witten, Phys. Rev. D30 (1984) 272.

[22] A. De Rujula and S. L. Glashow, Nature 312 (1984) 734.

[23] M. Ambrosio et al., MACRO Coll., hep-ex/9904031, EPJ C13 (2000) 453; hep-ex/0009002 (2000).

[24] D. Bakari et al., SLIM Coll., (Search for “light” magnetic monopoles), hep-ex/0003028 (2000).

[25] S. Coleman, Nucl. Phys. B262 (1985) 293.

[26] A. Kusenko, Phys. Lett. B405 (1997) 108.

[27] A. Kusenko and M. Shaposhnikov, Phys. Lett. B417 (1998) 99; A. Kusenko et al., Phys. Rev. Lett. 80 (1998) 3185.

[28] A. Kusenko et al., Phys. Lett. B423 (1998) 104.

[29] G. Giacomelli et al.(Magnetic Monopole Bibliography), hep-ex/0005041 (2000).